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# *SPACE SYSTEMS - STRUCTURAL DESIGN - STRESSES ANALYSIS REQUIREMENTS*



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# Foreword

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International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 3. Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

International Standard ISO 16454 was prepared by Technical Committee ISO/TC 20, Aircraft and Space Vehicles, Sub-Committee SC14, Space Systems and Operations.

Users should note that all International Standards undergo revision from time to time and that any reference made herein to any other International Standard implies its latest edition, unless otherwise stated.

# C O N T E N T

# 0. Scope

This WD is intended to be used for the determination of the stresses and margins of safety in launch vehicles and spacecraft primary structure design. Liquid propellant engine structures, solid propellant engine nozzles and solid propellant itself are not covered, but liquid propellant tanks, pressure vessels and solid propellant cases are in the scope of this WD.

This WD provides the requirements for maximum stresses and corresponding margins of safety determination when loads are once applied, and sets out the criteria for static strength failure modes such as rupture, collapse and detrimental deformation. Critical conditions associated with fatigue, creep and fracture mechanics are not covered. Notwithstanding those scope limitations the results of stresses calculations based on the requirements of this WD can be used for other critical conditions analysis.

In accordance with requirements fixed in this WD, models, methods and procedures for stresses determination can be also used for the strains, displacements, deformation calculations as well as for the loads definition applied to substructures and structure members of structures under consideration. When this WD applying, it is assumed that temperature distribution has been determined and is used as input data.

When ISO STD 14622 application is specified by a contract, load data must meet the requirements of ISO STD 14622, where only minimum values of design safety factors are established. Design safety factors used for stresses analysis and margins of safety determination may be larger and in that case their values shall be specified by a contract or accepted from appropriate experience. Recommendations on design safety factors application are presented in Appendix B.

When ISO DIS 14623 application is specified by a contract, load data for metallic pressurized systems and overwrapped pressure vessels must meet the requirements of ISO DIS 14623.

## 1.Applicable Documents

1.1. ISO STD 14622

1.2. ISO CD 14623

## 2. Definitions

2.1."A- basis allowable”.

The mechanical strength value above which at least 99% of the population of values is expected to fall, with a confidence level of 95%.

2.2. Allowable Load (Stress, Strain).

The maximum load (stress, strain) that can be accommodated by a material/structure without potential rupture, collapse, or detrimental deformation in a given environment. Allowable loads (stresses, strains) commonly correspond to the statistically based minimum ultimate strength, buckling strength, and yield strength, respectively.

2.3. Basic data.

Input data required to perform stresses analysis and to determine margins of safety.

2.4. "B-basis allowable”.

The mechanical strength value which at least 90% of the population of values is expected to fall, with a confidence level of 95%.

2.5. Collapse.

Failure mode under compression by quasi-static loads, when very rapid unevenly increasing irreversible deformations cause rupture after exceeding ultimate strain.

2.6. Composite material.

The combination of materials differ in composition or form on a macro scale. The constituents retain their identities in the composite. Normally, the constituents can be physically identified, and there is an interface between them.

2.7. Creep.

The process of a permanent material deformation, which is occurred during long time under the action of a constant or slowly altered loads. The ultimate creep deformation, corresponding to the loss of material integrity is often much higher than ultimate deformation in the case of short time loading.

2.8. Critical location

Structural member or the part of structure, which rupture, local buckling or detrimental deformation can lead as assumed to structure failure mode attainment earlier than in other locations for given loads combination.

2.9. Critical condition.

The most several environmental condition in terms of loads and temperatures or combination thereof imposed on structure, systems, subsystems and components during service life.

2.10. Destabilizing load.

The load that produces comprehensive stresses in critical location.

2.11. Development test.

A test to provide design information that may be used to check the validity of analytic technique and assumed design parameters, to uncover unexpected system response characteristics, to evaluate design changes, to determine interface compatibility, to prove qualification and acceptance procedures and techniques, to check manufacturing technology, or to establish accept/reject criteria.

2.12. Flight – type hardware test.

Test of flight structure article, protoflight model, representative special model or structure element fabricated with the same or close to flight hardware technology.

2.13. Gages.

Thickness and other structure dimensions which relative scattering could significantly influence on stress levels and/or margin of safety

2.14. Knockdown coefficient.

The empirical coefficient, other than design safety factor or uncertainty coefficient, which is used to determine analytically in a simple way actual or allowable loads or stresses and which is defined on the basis of flight-type structures, model structures or structural members test results in comparison with corresponding stresses analysis data.

2.15. Limit load

Maximum load that can be expected during service life and in the presence of the environment

2.16. Loads.

Concentrated and/or distributed over the structure surfaces or structure volume forces and moments caused by its interaction with environment and adjacent parts of vehicle, and accelerations. Pressures, external loads and enforced displacements acted at considered structure element, pretension, inertial loads caused by accelerations and thermal gradients are covered.

2.17. Loading case.

The particular condition described in terms of loads/pressures/temperatures combinations, which can occur for some parts of structure at the same time during its service life.

2.18. Local buckling.

Failure mode, which is realized when an alternative equilibrium mode of a structural member exists, and if occurred under loading could lead to detrimental deformation or rupture of that member. Local buckling is not considered as a failure mode when it is believed that the structure can properly operate during and after loading if an alternative equilibrium mode would occur.

2.19. Margin of Safety.

Margin of Safety (MS) = {Allowable Load / (Design Safety Factor * Limit Load)} - 1
NOTE: Load may mean corresponding stress or strain.

2.20. Minimum allowable.

Minimum material mechanical properties warranted by supplier.

2.21. Pressure.

An external load caused by fluids action on a structure surface.

2.22. Primary structure.

The part of the vehicle that carries the main loads and defines the fundamental resonance frequencies.

2.23. Rupture.

The loss of integrity by structure material differed from fatigue and ultimate creep deformation attainment, which can prevent the structure to withstand loads combinations.

2.24. Design safety factor.

The coefficient by which limit loads are multiplied in order to take into account the statistical variations of loads and structure resistance, and inaccuracies on the knowledge of their statistical distributions.

2.25. Semi-finished item.

The product which is used for structure manufacturing or assembling. The typical examples are sheets, plates, profiles, strips etc.

2.26. Stabilizing load.

Load which if applied in conjunction with destabilizing loads decreases comprehensive stresses.

2.27. Static strength.

The property of an structure, characterized by its possibility to withstand loads and temperatures combinations action without rupture, collapse, detrimental local buckling and detrimental deformation.

2.28. Strength failure mode.

The condition of a structure or structural member, which is considered as a critical condition in accordance with stresses analysis results.

2.29. Structure.

For the purposes of this standard it is primary structure, unit attachments, pressure vessels, loads carrying elements of appendages.

2.30. Structure mathematical model.

The analytical or digital presentation of a structure, which as assumed should provide adequate description of its response under loads/pressures/temperatures action.

2.31. Unit.

The part of vehicle which is designed mainly to provide vehicle functioning and differ from structure.

## 3. Requirements

### 3.1. General

For structures used in space systems such as launch and space vehicles, the stress analysis and corresponding margin of safety determinations for various static strength failure modes shall meet the requirements specified in this WD.

Basic data, structure models, methods for stresses analysis and strength criteria are considered as the integral parts of that procedure.

There are no limitations set out in this WD which restrict the application of results of stresses calculation for other purposes than those formulated below.

### 3.2. Basic data

Basic data used for the space structure stresses analysis shall meet the requirements of this clause. Basic data shall include all the following information:

- structure configuration, geometry and gauges, and
- structure materials and their properties, and
- loading cases list, loads and temperatures combinations, and corresponding design safety factors for every loading case.

#### 3.2.1. Structure configuration, geometry and gauges

3.2.1.1. Structure configuration, geometry and gauges data used for stresses analysis shall be correspondent to drawings representing for design stage.

3.2.1.2. Generally minimum thicknesses shall be used for stresses analysis.

3.2.1.3. Following exclusions are permitted from the requirement 3.2.1.2:

- when appropriate experience based on the results of flight - type hardware tests are available, nominal thicknesses may be used to determine critical loads for collapse and local buckling failure modes in conjunction with corresponding knockdown coefficients;
- for details with difficult form when stresses dependence on gages is not evident;

3.2.1.4. Structure configuration, geometry and gauges data must be sufficient to substantiate structure analytical model and to determine corresponding parameters.

3.2.2. Structure materials and their properties

3.2.2.1. Materials list, which are used for structure and its members fabrication, shall be correspondent to design and technology documentation. The information about sorts of materials, semi-finished items and technology processes must be sufficient to evaluate possible variations of their properties used for stresses analysis and margins of safety determination.

3.2.2.2. Material properties used for stresses analysis and margins of safety determination shall take into account manufactory processes, temperature and other significant environmental effects.

If appropriate data are not available special development tests shall be conducted to evaluate corresponding properties.

3.2.2.3. Appropriate ultimate and yield strength (for metal only) material properties shall be used for margins of safety calculations. "A-basis allowable” values shall be used where failure of a single load path would result in loss of structural integrity. Redundant structural elements where failure of one element would result in a safe redistribution of applied loads to other elements, "B-basis allowable” values may be used. It is permissible to use minimum allowable values warranted by material supplier.

Nominal modulus of elasticity and Poisson’s ratio shall be used for the stress analysis.

3.2.2.4. If inertia loads are applied and corresponding basic data are described in the terms of accelerations or gravity constant, inertia material properties and masses of units and appendages data must be sufficient to determine those inertia loads adequately.

Nominal material inertia properties and nominal units and appendages masses and parameters of their arrangements shall be used for stress analysis. When an attachment can be used for different types of units or appendages, then nominal values for the most unfavorable type of equipment shall be taken into account.

NOTE:

When equipment inertia scattering is considered as significant one, the most unfavorable combinations of units and appendages masses and parameters of their arrangements shall be used for local stresses analysis in areas near corresponding attachments.

3.2.2.5. Temperature effects on material and physical properties and thermal stresses shall be considered.

NOTE:

When appropriate experience is available, it is permissible do not take into account thermal stresses for materials with high ultimate deformation (in comparison with thermal expansion) and low yield strength.

3.2.2.6. When loading out of elastic limit is permitted, and loads values are sufficient to cause a significant material nonlinear behavior exhibition, corresponding stress - stain dependencies shall be used for stresses analysis.

3.2.3. Loading data

Load data must include:

- list of loading cases;
- loads and temperatures combinations for every loading case;

Load data must include the ranges in which loads and temperatures can alter simultaneously for every loading case and every loading combination. Maximum loads values shall be limit loads.

3.3. Structure mathematical model

3.3.1. General.

When applied for stresses analysis the structure mathematical model generally shall be developed by using appropriate experience based on the results of flight-type hardware tests.

If such experience is not available or considered as not applicable to a particular case, special development tests shall be conducted for structure model validation.

The structure mathematical model shall be developed to take into account the structure configuration, materials applied, loading and environmental conditions.

3.3.2. Boundary conditions.

Boundary conditions is an integral part of the structure analytical model. The adjacent structures influence on loads transmission, stresses distribution and collapse mode shall be evaluated to provide adequate loading conditions of the structure under consideration. When any applied boundary conditions do not represent the actual stress distribution, adjacent structure or sufficient large part of adjacent structure analytical model shall be developed and incorporated into the model of the structure under consideration.

Notwithstanding that requirement, simplification of boundary conditions is permitted, such as reducing to conservative conditions or to effective stiffnesses, however it shall be demonstrated that those simplifications provide conservative result.

In general the adjacent structure model development requirements are the same as for the structure under consideration except only stiffnesses and loads transmission should be modeled properly.

### 3.4. Structure mathematical model check

When numerical methods are used for stress analysis, the following structure mathematical model tests shall be conducted in maximum possible extent in frames of used software possibilities:

a)Mass check

It shall be checked that the total mass of the mathematical model is not differ from mass indicated in approved system documentation more than of 0.2%

b)Center of gravity check

It shall be checked that the center of gravity of the mathematical model are not differ from center of gravity indicated in approved system documentation more than of 1.0% of maximum structure analyzed dimension

c)Inertia check

It shall be checked that inertia tensor elements values of the mathematical model are not differ from values indicated in approved system documentation more than of 1.0% of maximum inertia tensor elements value

d)Free-free check

To conduct this check lower frequencies of the mathematical model shall be determined. It shall be checked that at least 6 frequencies are presented with absolute values not higher then 0.005 Hz. If more then 6 quasi-zero frequencies are presented, than it shall be explained by specific structure configuration

d)Strain energy check

To conduct this check, rigid body modes corresponding to quasi-zero frequencies (see p. “d” above) shall be determined for the mathematical model with free-free boundary conditions. Modes shall be normalize so that displacements are equal 1 meter and rotations are equal 1 radian. Strain energy matrix shall be defined as

$$E=1/2\ \Phi^T K \Phi,$$

where Φ is the matrix with rigid body modes as columns and K is the stiffness matrix of the mathematical model.

It shall be checked that diagonal elements of matrix E are not higher than $10^{-3}$ N*m

e)Gravity load check

Gravity load of 1 “g” value shall be applied consequently along each axis of the used Cartesian coordinate system for the mathematical model with boundary conditions, correspondent to required stress analysis. It shall be checked that total reaction for corresponding direction is equal to the mathematical model weight. It shall be also checked that at any boundary point desirable reactions are presented in desirable directions.

f)Thermal check

This check is conducted for the mathematical model with free-free boundary conditions and in the absence of rigid links between nodes, which prevent any relative deformation of these nodes. Uniform temperature field $\Delta T=100$ K shall be applied to the mathematical model. The Poison’s ratio of 0.3 and thermal expansion coefficient of $\alpha=10^{-5}$ shall be used for this check. It shall be checked that resulting stress is negligible at any structure location

g)Artificial stiffening check

If artificial stiffening is used in the mathematical model for the specific purposes, it shall be checked that it does not cause unrealistic vibration modes arising.

h)The node ratio check

To conduct this check maximum and minimum diagonal elements of stiffness matrix shall be determined for each node of the mathematical model. It shall be checked that the ratio of minimum value to maximum one is higher than $10^{-8}$ for any node.

i)Maximum ratio check

To conduct this check the mathematical model stiffness matrix shall be normalized as

$$K=LDL^T,$$

where L is triangle matrix and D is diagonal matrix.

The ratio (K diagonal element)/(corresponding D diagonal element) shall be determined for each row of stiffness matrix. It shall be checked that the ratio is lower than $10^7$ for any row of stiffness matrix

### 3.5. Failure modes

#### 3.5.1. General

The strength criteria application shall be based on the appropriate experience including flight-type hardware testing with accounting for basic data, structure model, knockdown coefficients and fabrication technology. When appropriate experience is not available or in case of doubt, special development tests shall be conducted for criteria validation.

#### 3.5.2. Yield strength

Margins of safety for yield strength condition (metal structures only) shall be determined for any loads combination presented in loading data with following exclusions:

- permanent deformations are not considered itself as critical condition, and
- permanent deformation does not impact the structure performance.

It is considered that yield failure mode is realized when stress at any location of the structure is equal to or more than corresponding material yield strength.

#### 3.5.3. Rupture

Margins of safety for rupture failure mode shall be determined for any loads combination presented in loading data.

It is considered that rupture failure mode is realized when stress (strains) levels in any location of the structure are equal to or more than corresponding ultimate material properties.

#### 3.5.4. Collapse

Margins of safety shall be determined for collapse failure mode if comprehensive stresses can occur, when loads alter in specified ranges.

Criterion for this failure mode is the indication of proper buckling analysis, that collapse is realized for given loads combination. For collapse analyses the initial deformations due to manufacturing shall be taken into account. It is permissible to take them into account by applying of corresponding knockdown coefficients.

#### 3.5.5. Local buckling

Margins of safety for local buckling of all structural parts shall be determined if comprehensive stresses can occur in these parts, when loads alter in specified ranges. If the margin of safety is smaller than zero for a part (parts) of the structure and local buckling is considered as permissible itself, margins of safety for other failure modes shall be determined with accounting for buckled elements.

Criterion for this failure mode is the indication of proper buckling analysis, that local buckling is realized for given stresses combination. For local buckling analyses the initial deformations due to manufacturing shall be taken into account. It is permissible to take them into account by applying of corresponding knockdown coefficients.

## 3.6. Analysis methodology and software

### 3.6.1. Analysis methodology

3.6.1.1. Either closed form structural analysis techniques or numerical methods, such as finite element, boundary element methods, etc., may be used for stresses analysis and margins of safety determination separately or together (for example, stresses are calculated by using numerical method, and margins of safety corresponding to structural member local buckling are determined from an analytical result).

3.6.1.2. In case of numerical methods application the required accuracy shall be demonstrated.

3.6.1.3. Generally methods used for stresses analysis shall be verified by successful application to structure design including comparison between results of calculations and results of tests.

### 3.6.2. Software verification.

3.6.2.1. Software used for stresses analysis must be verified by comparison results of calculation with theoretical results and (or) results obtained by using other verified software.

3.6.2.2. Verification procedure shall take into account typical structure models, boundary conditions, loading conditions, materials applied, convergence and stability of numerical methods used.

When knockdown coefficients are used as an input data for software application, verification must be conducted without their accounting for to provide the comparison with pure theoretical results.

## 3.7. Critical location analysis.

Loading conditions and stresses distribution analysis shall be carried out to define critical locations where material or structural members are most sensitive to a failure mode attainment.

The most unfavorable combinations of loads and temperatures in frames of specified ranges shall be accounted when margins of safety are determined for every critical location.

### 3.8. Margins of safety determination

3.8.1. Margins of safety (MS) shall be calculated by the formula (3.8.1.1):

$$MS = AL / (f*LL) - 1 , \qquad (3.8.1.1)$$

where:

AL : allowable load under specified functional conditions (e.g. yield, rupture, collapse, local buckling), which shall be determined in accordance with criteria stated in the clause 3.5 and requirements of the clause 3.2.

LL : limit load

f: design safety factor.

In Appendix A an example of application is presented for the case of several loads combination.

NOTE: Margins of safety express the margin of the design load (f*LL) against the allowed load. Loads can be replaced by stresses if the load-stress relationship is linear.

3.8.2. For collapse and local buckling failure modes stabilizing loads shall be accounted in conjunction with design safety factor 1.0. If otherwise specified, minimum values of stabilizing loads (in the prescribed ranges) shall be used instead of DL in this case.

3.8.3. Margins of safety, calculated in accordance with equation (3.8.1.1), shall be non-negative for every loading case and loading combination specified in basic data to demonstrate that structure meet strength requirements.

3.8.4. As an alternative approach reserve factor ($\eta$) may be determined by the equation (3.8.4.1).

$$\eta = AL / (f*LL) = MS + 1 . \qquad (3.8.4.1)$$

The requirement $\eta \geq 1.0$ is mathematically equivalent to the requirement formulated in the clause 3.8.3.

### 3.9. Report.

As a result of the stress analysis activity a stress analysis report shall be issued. The report shall consist of :

- Basic data, including:
  - Structure configuration, geometry and gauges
  - Structure materials and their properties
  - Limit loads/pressures/temperatures for every loading case considered
  - Safety factors for every loading case and structure elements considered
- Structure mathematical model description, including:
  - Rationales for its choice
  - Boundary conditions
- Structure mathematical model checks and their results
- Failure modes considered
- Strength criteria applied
- Description or references to methods and software applied
- Summary of significant analysis results including the table of margins of safety (or reserve factors) for every loading case and structure elements considered.

The analysis shall be revised and updated whenever changes of basic data could occur, stress analysis report shall be revised to take into account corresponding results.

# APPENDIX A

(Informative)

Margin of safety determination example for the case of several loads combination

A.1. When loads combination is applied to a structure, it is assumed that all loads alter from zero simultaneously and proportional to some parameter $\lambda$. When this parameter equals 1.0, it is correspondent to design loads combination. In the case of collapse and local buckling stabilize loads should be accepted not altered and equaled to prescribed values. Margin of safety is determined by the equation (A.1):

$$MS = [\, \lambda \,] - 1\ , \qquad (A.1)$$

where

[ $\lambda$ ] – value of the parameter $\lambda$, corresponding allowable loads combination (loads combination when critical condition is realized)

In the case of doubts that ultimate loads combination could not be the most unfavorable one (e.g., when structure exhibits significant nonlinear behavior and/or essentially nonlinear strength criteria are applied) the MS sensitivity should be investigated to ultimate loads values variations inside prescribed ranges and minimum MS is determined.

A.2. When the combination of loads application can be substituted by an application of one load, which is a function of other loads and is considered as equivalent one, this load can be used in the equation (2.7.2.1) for margin of safety determination. Typical example is an equivalent axial load ($N_E$) for the case of axial load (N) and bending moment (M) application to cylindrical shell of diameter D:

$$N_E = N + 4M/D \text{ (tension)}\ , \qquad (A.2)$$

$$N_E = N - 4M/D \text{ (compression)}$$

A.3. When the combination of loads application can be described at the critical location by some equivalent specific load (flux), which is a function of loads, this flux can be used in the equation (2.7.2.1) for margin of safety determination. Typical example is the case of axial load (N) and internal pressure (P) application to cylindrical shell of diameter D:

$$\text{flux} = N/\pi D + P{*}D/4 \text{ (for axial stresses)} \qquad (A.3)$$

# APPENDIX B

(Informative)

Minimum Design Safety Factors

Minimum design safety factors used for stress analysis are presented in this Appendix. General requirements are presented in ISO STD 14622.

B.1 Design safety factors philosophy implies an application of experience, which is based mainly on expert's decisions. The application of design safety factors is the integral account of many different issues such as loads statistical distributions, accuracy of loads and stress analysis models, manufactory technology level, possibility of test methods and facilities to provide adequate loading conditions, etc.

B.2. Design safety factors for yield critical mode analysis are presented in the Table B.1.

Table B.1. Minimum Yield Design Safety Factors (yield critical mode)

| Type of structure | Type of Load | | |
|---|---|---|---|
| | Internal Differential Pressure | External/Inertia/Functional Load | Thermal Loads/Temperature Stress [1)] |
| All types | 1.0 | 1.0 | 1.0 |

NOTE:
1. If thermal loads shall be considered in accordance with particular applied stress analysis requirements

B.2. Design safety factors for rupture/burst, collapse, local buckling critical modes analysis are presented in the Table B.2.

Table B.2. Minimum Ultimate Design Safety Factors
(rupture/burst, collapse, local buckling critical modes) [4,5,6,7,8]

| Type of structure | Type of Load | | |
|---|---|---|---|
| | Internal Differential Pressure | External/Inertia/Functional Load [3] | Thermal Loads/Temperature Stress [1,2] |
| Unmanned Mission Structure/Pressurized Structure | 1.25 | 1.25 | 1.0 |
| Manned Mission Structure/Pressurized Structure | 1.4 | 1.4 | 1.0 |
| Unmanned Mission Pressure Vessel | 1.5 | 1.25 | 1.0 |
| Manned Mission Pressure Vessel | 1.5 | 1.4 | 1.0 |

NOTES:
1. If thermal loads shall be considered in accordance with particular applied stress analysis requirements
2. If thermal loads produce compression stress, which could lead to collapse/local buckling mode, design safety factor for external loads should be applied
3. External differential pressure is included.
4. In case of collapse/local buckling critical modes ultimate design safety factor 1.0 should be applied for stabilizing loads/pressures.
5. For composite materials with high ultimate properties scattering additional design safety factor 1.2 is applied as a multiplier to presented in the Table B.2 ones.
6. For structure elements used for connections (bolts, fittings, etc.) additional design safety factor 1.25 is applied as a multiplier to presented in the Table B.2 ones.
7. Pressure components are not considered.
8. Lower safety factors can be applied for abnormal loading cases and when acceptable structure failure probability can be demonstrated with accounting for structure allowable loads statistical model based on flight-type specimens tests results.